APOLLO MISSION ANALYSIS FOR RADIATION

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Abstract

In an attempt to find significant shortcomings in Apollo vehicles, an analysis of the LOR mission for radiation effects on crew safety and mission success has been made. The study has been prompted by certain vehicle design features which are under review at this time. The results of the radiation study are presented in the form of curves of crew safety and mission success probability as they depend upon the choice of certain acceptable dose values. Mission success probability for a 24 hour lunar stay is found to be about 0.98. Crew safety from radiation hazard alone is estimated to lie between 0.990 and 0.995. Both of these probabilities are for a range of allowable dose values of 50 to 150 rads at the blood formation level in the body and 500 to 1500 rads to the skin. The confidence limit is 90%.

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I. Crew Safety, Mission Success, and Allowable Dose

For this study the following definitions were adopted.

Crew Safety (CS) - requires return of the crew to earth without the appearance of measurable disabilities within 60 days. A disability such as nausea suffered by the crew during flight would certainly impair performance and is to be considered in the category of crew safety factors.

Mission Success (MS) - requires a safe lunar landing, a stay of approximately 24 hours and safe return to earth. Note that mission success includes crew safety. The chief difference will be the occurrence or anticipated occurrence of an event which causes the lunar stay to be greatly abbreviated or not attempted at all.

We shall not attempt to define precisely an allowable dose. However, it is reasonable to consider doses 4 cm deep in the body between 50 and 150 rad as being potentially if not certainly disabling. Similarly, astronaut skin doses in the range 500 to 1500 rad could perhaps cause sufficient disability to endanger a pilot's performance.* Thus we shall calculate the probability of receiving doses spanning each of these ranges in order to evaluate the crew safety risk. The attempts to avoid such doses cause additional lowering of mission success. In this way we leave for the biophysicist the precise dose determination and we also illustrate the sensitivity of our results to the dose.

The following is an outline of the significant events which may occur:

Crew Safety Items

(1) A large solar flare particle event may occur while the crew is in the command module. No abort is assumed possible. The crew is exposed for the entire event, which it is assumed may begin on any one of 5 days.

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* A useful review is by W.H. Langham, "Some Radiobiological Aspects of Early Manned Space Flight," Proceedings of Lunar and Planetary Exploration Colloquium, Vol. III, #2, May 1963.

(2) A large event may begin while the lunar surface exploration is in progress, reaching such a high rate so rapidly that an abort procedure requiring 6 hours to reach the command module is inadequate. That is, a critical dose rate $\frac{D}{6}$ rads/hour is exceeded, where D is an assumed limiting dose. It is assumed that such circumstances may arise during one 24 hour period of the mission.

Mission Success Items

(1) A dose rate not quite as high as that considered above, e.g. D/24, may still require either premature departure from the lunar surface or it may prevent a landing attempt. These possibilities may be handled together by assuming a two day period of vulnerability to such high rates.

(2) Both crew safety items above are also mission success items.

Note that the above assumptions are consistent with the following abort rule:

> When the indicated dose rate, either at the skin or 4 cm deep in the body, exceeds the critical dose level in rads divided by 24, an abort is called for. If the landing has already been made, the mission must leave the lunar surface. If not, the landing is cancelled and the mission returns to earth.

We also note that no sophisticated warning or prediction is assumed beyond a relatively simple skin and depth dose rate meter.

Since the expected dose from two passages through the radiation belts is small compared to solar event doses and not probabilistic, we have concentrated our attention on the radiation hazard of solar cosmic rays.

II. Models and Shield Calculations

The recent solar flare proton compilation by Webber* is used. This is essentially an updating of the compilation in the Solar Proton Manual. It includes a rather detailed list of solar cosmic ray events with current best estimates of peak and integral particle fluxes and rigidity spectra. The 1956-61 period is covered. We have adopted the values therein for total

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* An Evaluation of the Radiation Hazard Due to Solar Particle Events, by W.R. Webber, Boeing Co. Document D2-90469, Dec. 1963.

proton flux per event, peak proton flux rate when available, and characteristic rigidity determining the spectral shape. Equal numbers of protons and alpha particles per unit rigidity interval are assumed. A computer program has been written by E.N. Shipley and has been used to calculate for each event the particle dose in human flesh for various depths in tissue and for various thicknesses of spherical shell aluminum shield. The program also will compute the dose within a composite structure such as the command module. The September 1963, 153 term description provided by NAA has been used here. Capsule center doses are calculated in all cases.

For lunar surface calculations we assume a space suit thickness of 0.15 gm/cm^2, and a lunar shadowing factor which reduces the dose by one-half.

Thus for each of the solar particle events exceeding 10^7 protons/cm^2 above 30 MeV according to the Webber compilation, we have computed the total dose in the command module. For events with peak dose rates above 100 protons/cm^2 sec above 30 MeV, we compute dose rates when in the space suit on the lunar surface. This has been done for both protons and alpha particles of the same rigidity distribution. We have calculated these doses both at the astronaut skin and 4 cm deep in his flesh, the latter assumed roughly representative of blood formation organs and the digestive tract lining.

The resulting curves are shown in cumulative form in Figures 1 through 4. We include a smoothed 90% confidence boundary based upon an assumed Poisson distribution of events.* These 90% curves are those which are actually used in the following to evaluate the various risk probabilities.

III. Evaluation of Crew Safety and Mission Success Probabilities

As has been suggested above, we now consult the curves of probability per mission that a given dose is exceeded. The elements of the computation are shown in Tables 1 and 2.

Two classes of dose are carried for both CS and MS purposes, i.e. skin and 4 cm deep in tissue. In the resulting curves of probability per mission vs. allowable dose we have shown the individual components of the total risks. We refer to Figures 5 and 6. Where no observed event in the input data would have produced the dose under consideration, the probability quoted is based upon Leibowitz' analysis of 90% confidence limits.

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* M.A. Leibowitz, Bellcomm TM-1112-1, March 6, 1964.

Such data is plotted with dotted lines to indicate the extrapolation and the doses due to the largest event seen in each case are indicated by the small squares in Figures 5 and 6.

The above analysis is subject to several criticisms. One is the simplified mission profile assumed, with only four items contributing to our CS-MS evaluation. Indeed, other abort modes may exist which have not been considered. For example, the suggestion has been made that the command module might be placed in lunar orbit, apex down, to achieve nearly a factor of three dose reduction.

We have used dose rates for analysis of the lunar stay portion of the mission. This approximation is certainly all right within a factor of two; probably much better than that. Simplicity is the chief argument favoring the method.

The model events used are the best available. However, the total number of particles and the characteristic rigidity of each event are uncertain by about two. The events themselves have been treated as randomly occurring in time with no correlation from event to event and with a large factor required to achieve 90% confidence in frequency observed. Finally, the data are all derived from 1956-1961, the active half of sunspot cycle 19. Correlation between spot number and solar cosmic ray event has not been made, nor do we at this time have the ability to describe cycle 20 in either sunspot or solar cosmic ray activity level.

There has been no warning system assumed beyond the simple dosimeter which in this case calls for an abort from the lunar surface when the observed dose rate if continued for 24 hours would exceed a given dose limit. More sophisticated warning systems would of course be capable of improving crew safety probability, but their effects on mission success could be either positive or negative, depending upon false alarm characteristics. In view of the limited CS risk during the lunar surface portion of the mission, a warning system must be very carefully evaluated before it is adopted.

IV. Conclusions and Recommendations

Perhaps surprisingly, mission success probability is equal to or greater than 0.98. It should be noted that mission success required a full 24 hour lunar stay.

It will be seen that the probability of an excessive skin dose dominates mission success while the astronauts are on the lunar surface. We have been conservative here by neglecting the Lunar Excursion Module shielding. It is expected that each astronaut will spend roughly half his lunar stay within the vehicle and its minimum thickness is approximately 0.2 gm/cm^2. This would reduce the skin dose rate by approximately

two and this, in turn, implies approximately one half the probability of MS failure due to skin dose on the lunar surface. A more careful study of this portion of the mission with the detailed LEM design at hand is planned.

Crew safety is perhaps in a less satisfactory state than mission success seems to be. 50 rads is not out of the question as a limiting 4 centimeter dose, and this implies crew safety probability of about 0.99. Nor is it obvious what action must be taken to improve this. NAA have estimated only 40% reduction in dose for an additional 140 pounds of spot shielding.* With our present knowledge of the solar events this only provides roughly a 30% decrease in crew risk. This is chiefly because of the limitations presented by the 90% confidence limits which indicate a constant non-zero probability of occurrence for increasingly larger solar cosmic ray events. Nevertheless, intuitively one expects a reduced probability for larger events and for this reason alone would recommend that radiation shielding studies be continued. The rearrangement of onboard equipment is desirable, chiefly because of its effects upon body doses at points other than capsule center.

It is clear that this matter is worth further study, as is the gathering of more solar cosmic ray data. In particular as the coming cycle (20) develops it will be of great utility to compare the general activity level with that of cycle 19.

Another matter of continuing importance is the search for possibly radiosensitive equipment items. This is already receiving attention at North American. It should be encouraged at Grumman, especially since otherwise the feeling that an abort is the only LEM defense against radiation tends to dominate.

Acknowledgment

Extensive consultation with E.N. Shipley and the results of his dose calculations have contributed materially to this report.

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* F. Raymes

TABLE 1 - RISK TO CREW SAFETY

Mission Portion	Dose, Rads	Location	Dose Rate Rads/Hour	Probability Per Day From Figs. 1-4	Duration of Portion, Days	Risk Probability
Translunar & Transearth - Astronauts in Command Module	50	4 cm deep		0.0018	5	0.0090
	100	4 cm deep		0.0012	5	0.0060
	150	4 cm deep		0.0011	5	0.0055
	500	skin		0.0011	5	0.0055
	1000	skin		0.0011	5	0.0055
	1500	skin		0.0011	5	0.0055
On Lunar Surface; Astronauts in 0.15 gm/cm^2 Suits 6 Hour Dose Disabling	50	4 cm deep	8.3	0.0011	1	0.0011
	100	4 cm deep	16.7	0.0011	1	0.0011
	150	4 cm deep	25	0.0011	1	0.0011
	500	skin	83	0.0028	1	0.0028
	1000	skin	167	0.0012	1	0.0012
	1500	skin	250	0.0011	1	0.0011
Total Crew Safety Risk	50	4 cm deep				0.0101
	100	4 cm deep				0.0071
	150	4 cm deep				0.0066
	500	skin				0.0083
	1000	skin				0.0067
	1500	skin				0.0066

TABLE 2 - RISK TO MISSION SUCCESS

Mission Portion	Dose, Rads	Location in Body	Dose Rate Rads/Hour	Probability Per Day From Figs. 1-4	Duration of Portion (Days)	Risk Probability
Approaching or Already Made Lunar Landing - Abort if Dose/24 is Exceeded	50	4 cm deep	2	0.0028	2	0.0056
	100	4 cm deep	4	0.0015	2	0.0030
	150	4 cm deep	6	0.0011	2	0.0022
	500	skin	20	0.0078	2	0.0156
	1000	skin	40	0.0055	2	0.0110
	1500	skin	60	0.0040	2	0.0080
Crew Safety Risk as Per Table 1 for CM only	50	4 cm deep				0.0090
	100	4 cm deep				0.0060
	150	4 cm deep				0.0055
	500	skin				0.0055
	1000	skin				0.0055
	1500	skin				0.0055
Total Mission Success Risk	50	4 cm deep				0.0146
	100	4 cm deep				0.0090
	150	4 cm deep				0.0077
	500	skin				0.0201
	1000	skin				0.0165
	1500	skin				0.0135

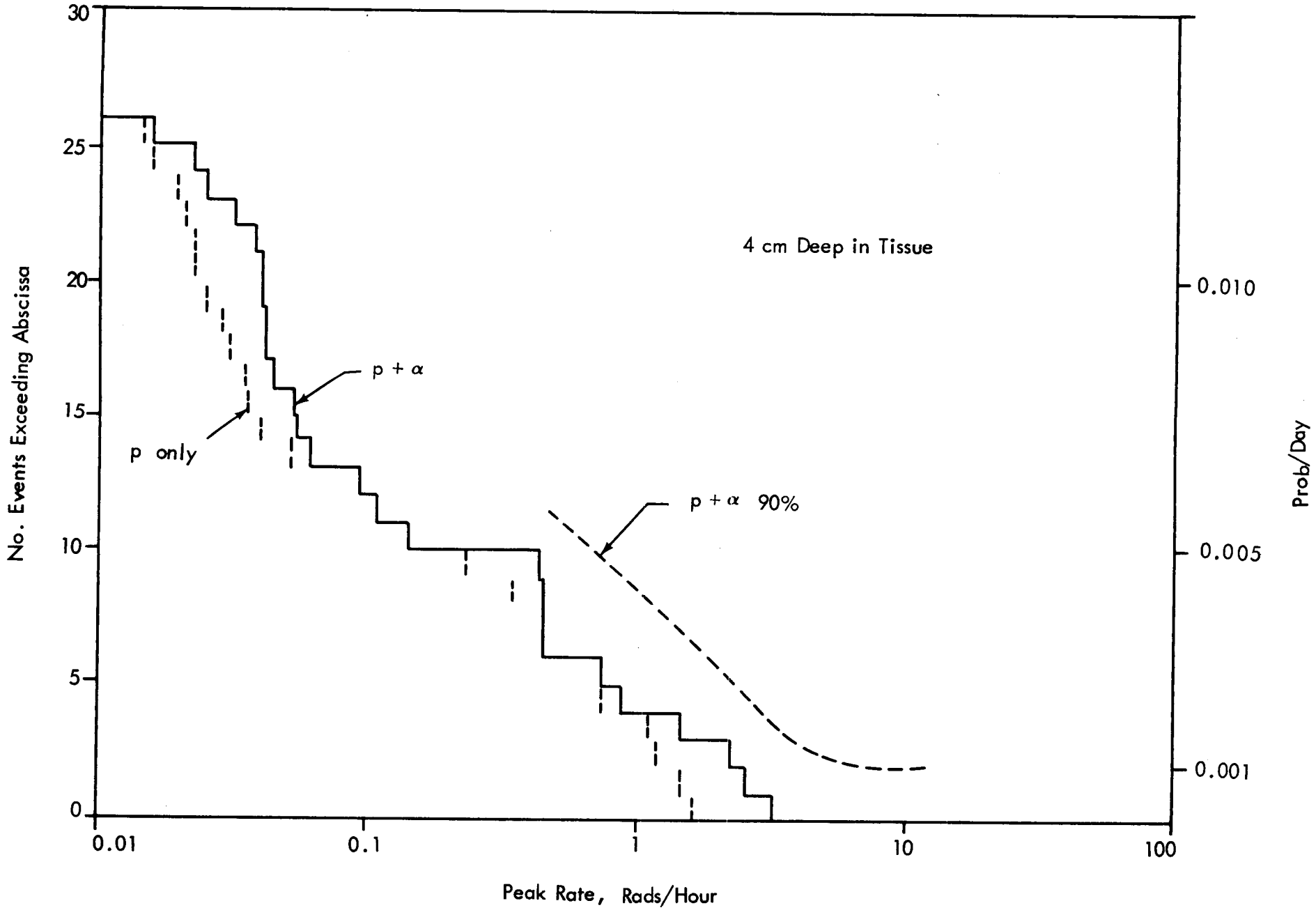


FIGURE 1 PEAK DOSE RATES ON MOON UNDER 0.15 CM/CM^2

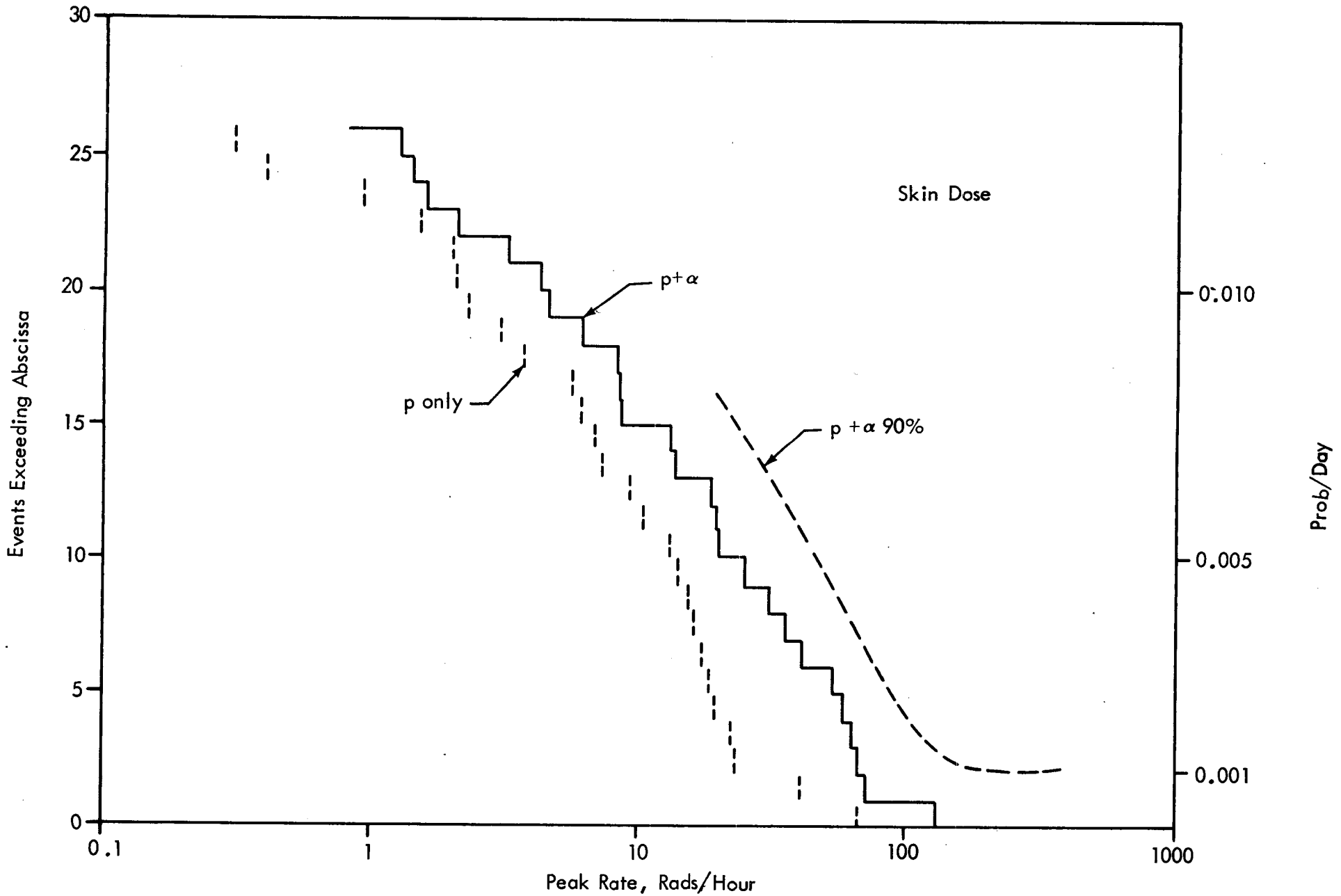


FIGURE 2 PEAK DOSE RATES ON MOON UNDER 0.15 CM/CM^2

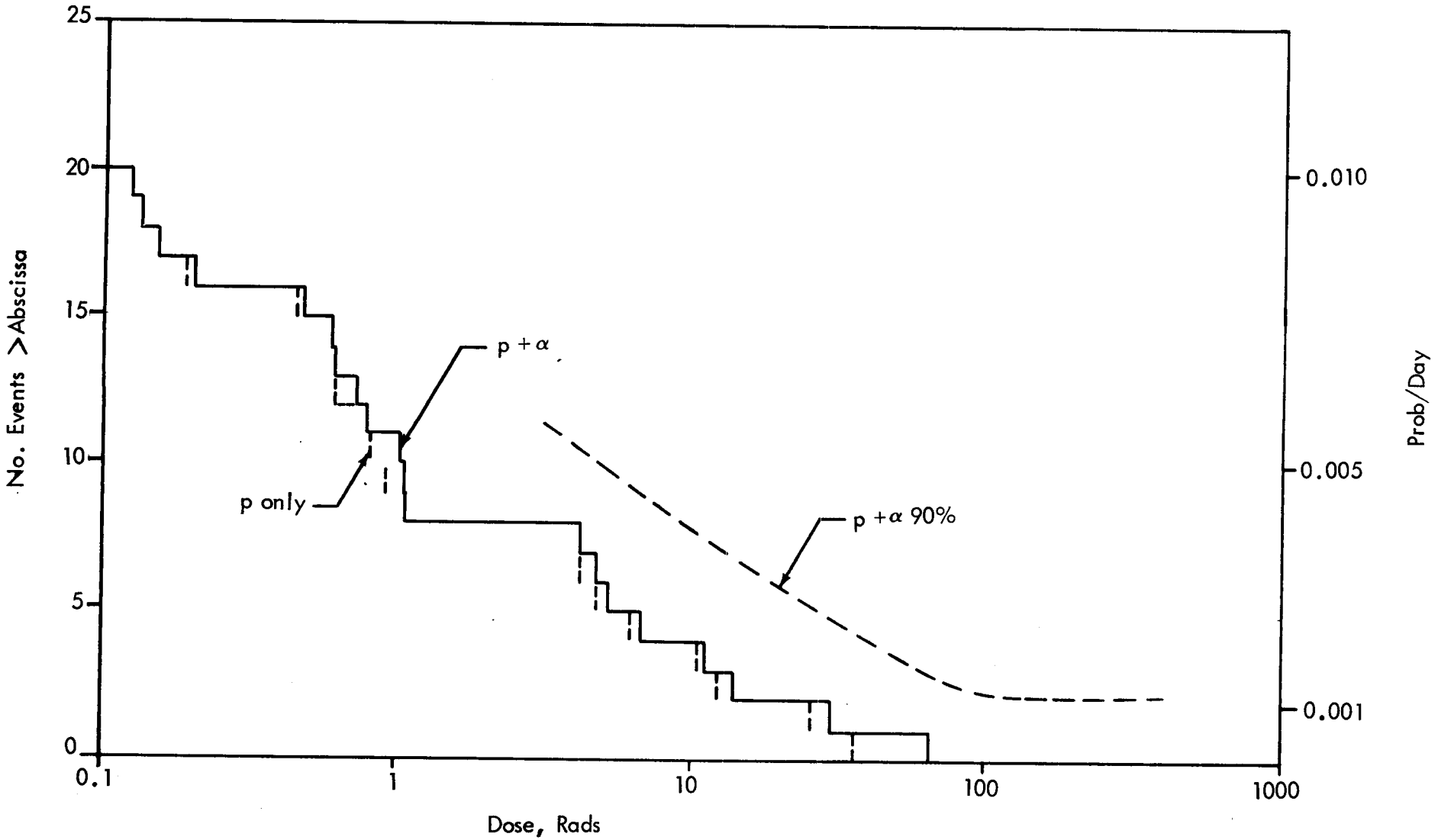


FIGURE 3 DOSE FOR ENTIRE EVENT 4 CM DEEP IN TISSUE, SEPT. 63
COMMAND MODULE

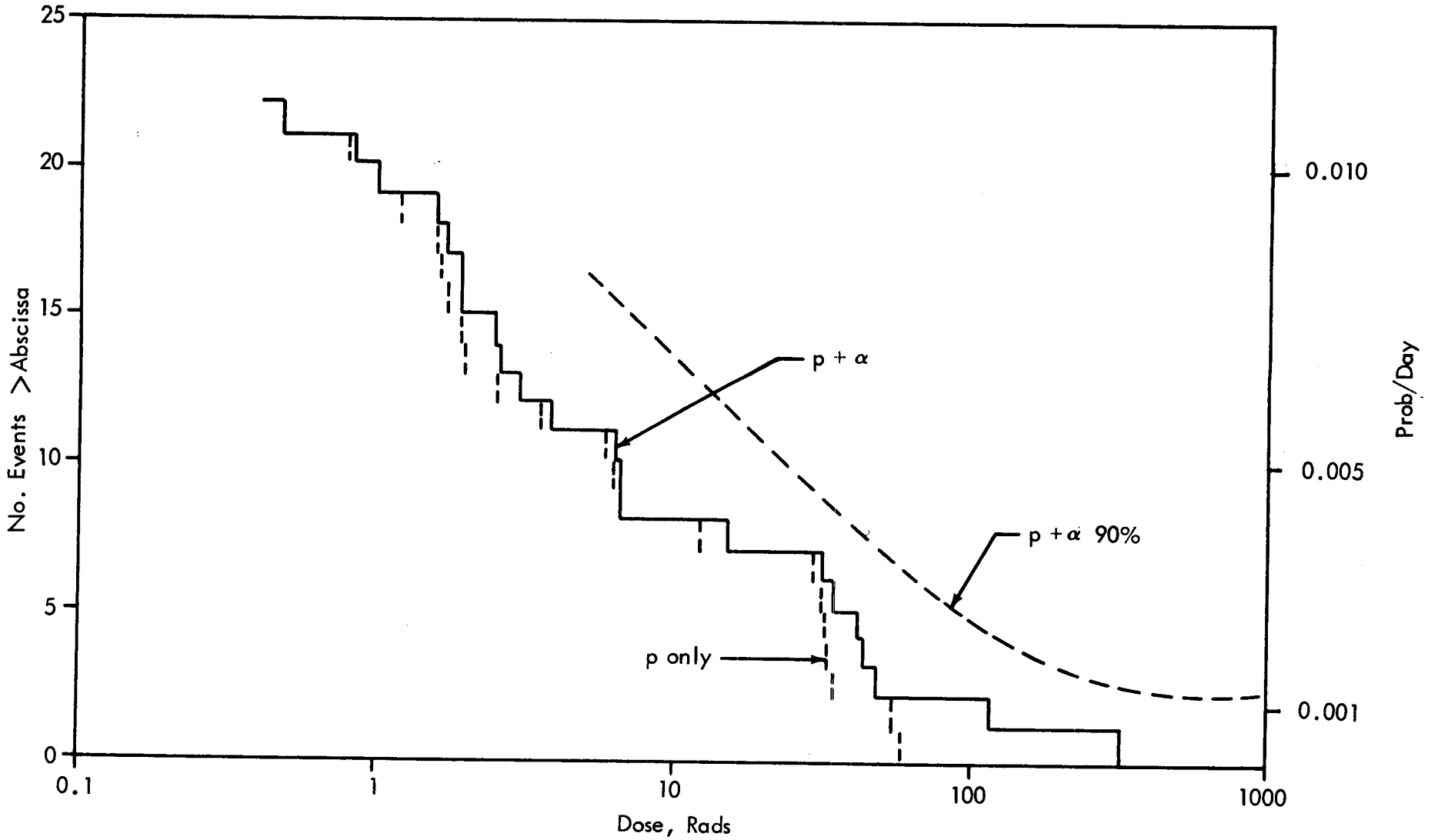
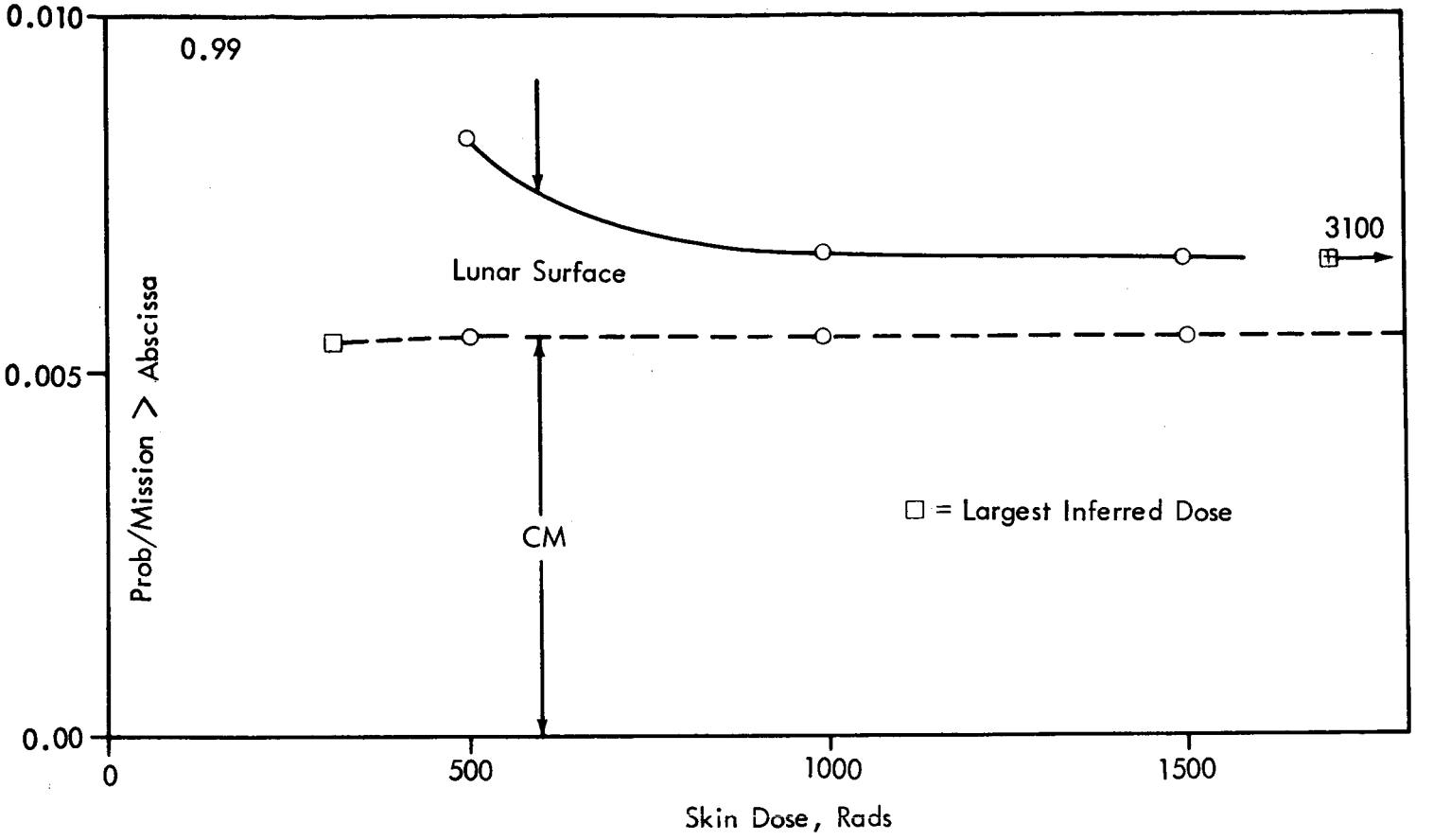


FIGURE 4 SKIN DOSE FOR ENTIRE EVENT SEPT. '63 COMMAND MODULE



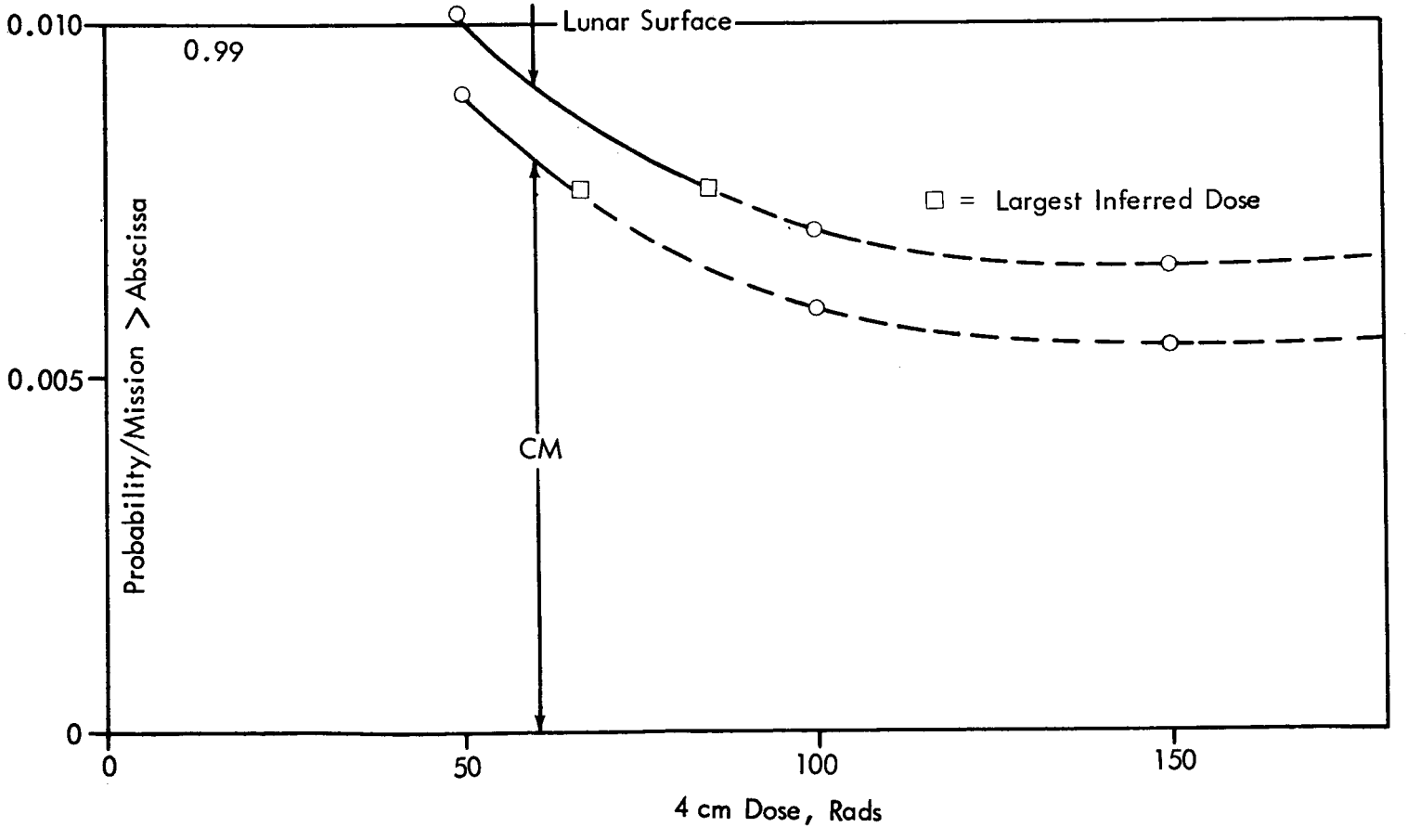
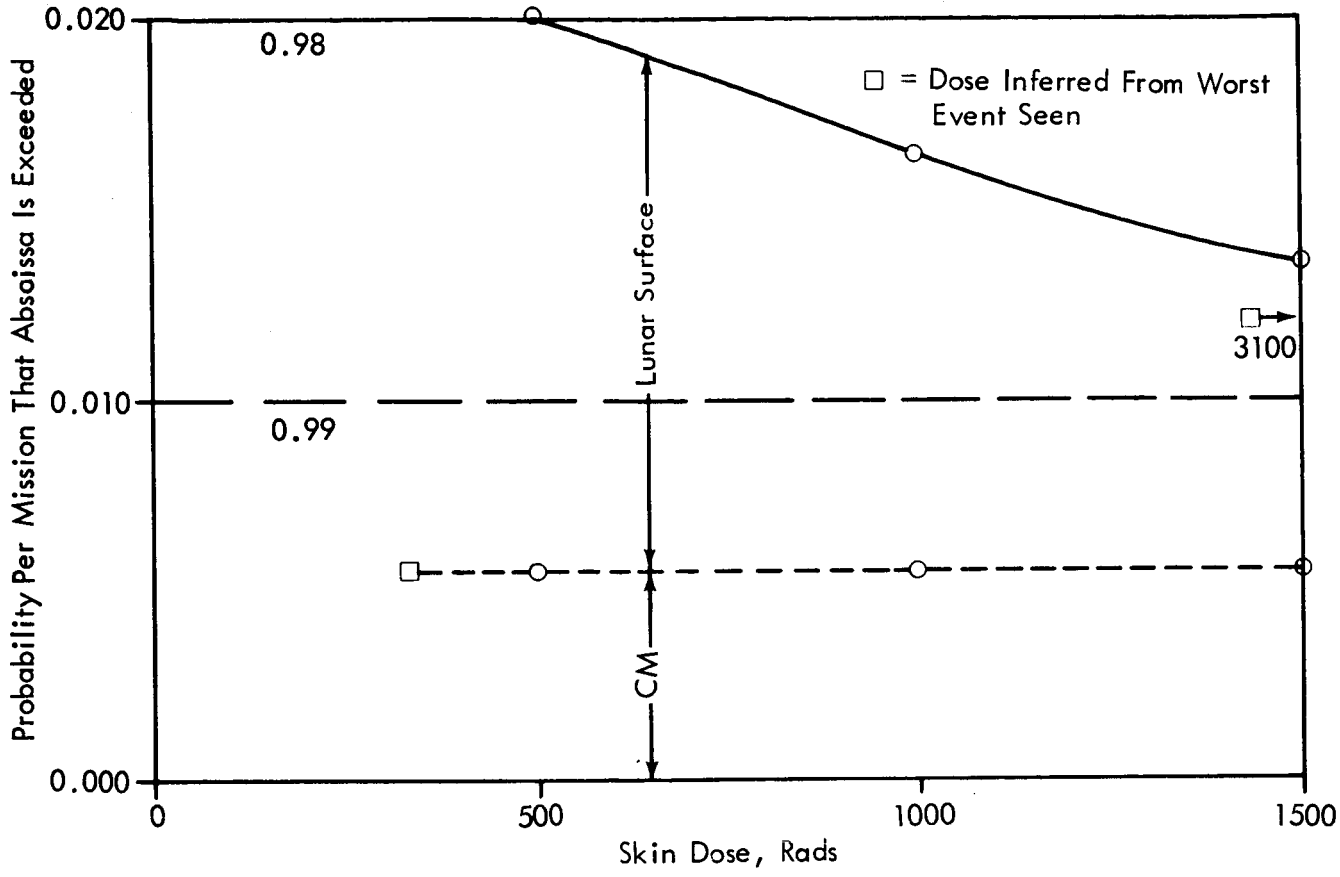


FIGURE 5 CREW SAFETY



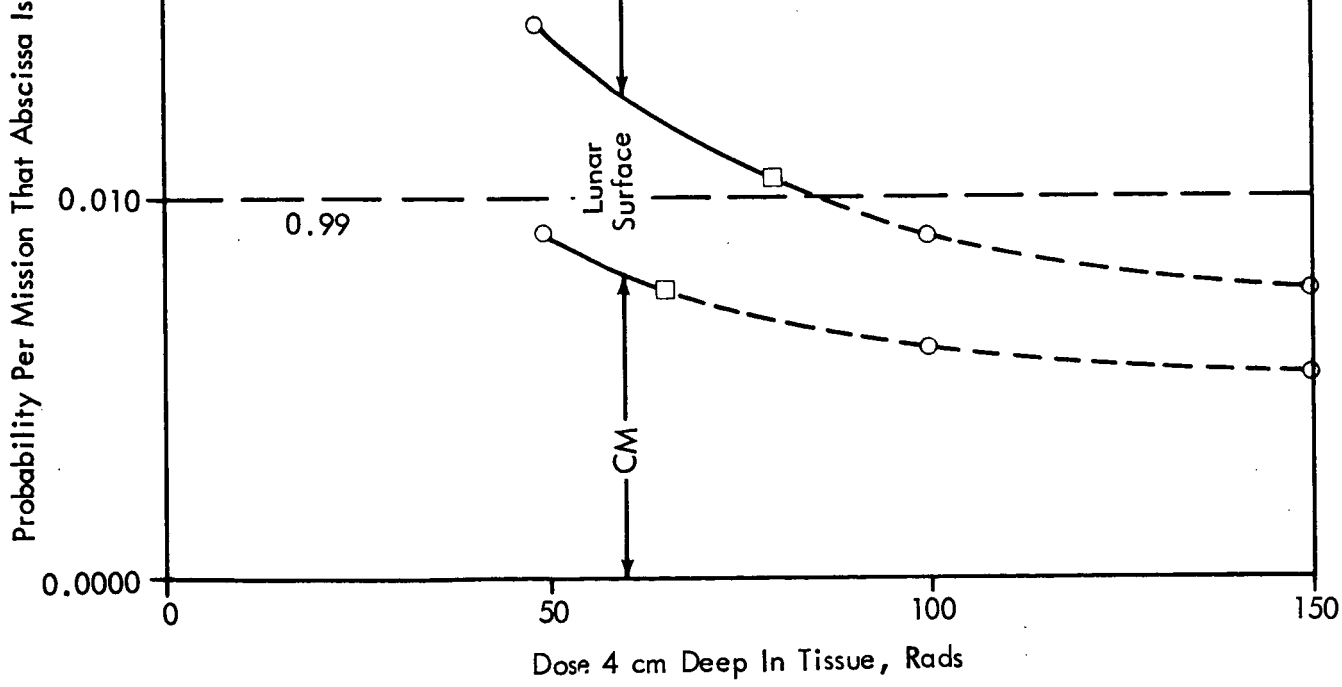


FIGURE 6 RISK TO MISSION SUCCESS SKIN DOSE